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The effect of cutting conditions on the friction angle

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The Effect of Cutting Conditions
on The Friction Angle (τ)

by

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The first is Professor George E. Kane, my thesis advisor, who gave me continual guidance throughout the entire thesis. The next is Mr. Raymond Grund, the technician in the Manufacturing Processing Lab, who helped me take and record the data. Then, there is Professor Sutton Monro, who gave his time and talent in analyzing the data; and Mr. Gary Whitehouse, who manipulated the data into a form usable by the LGP-30 Computer, and who then ran the computer.

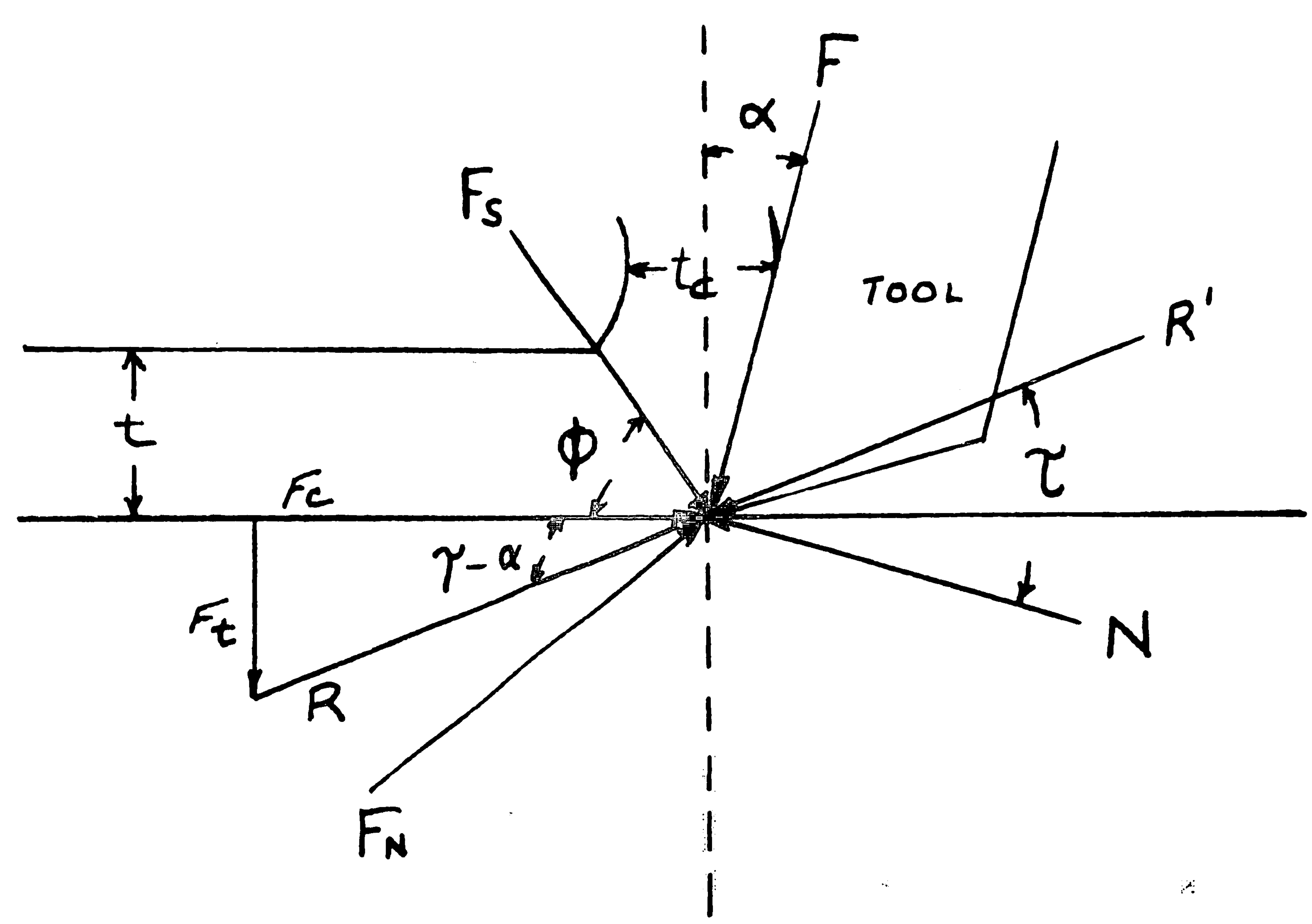
Last, but not least, I would like to thank my wife, Judy, for typing my thesis.

Table of Contents

Area of Study

The area of this study is limited to two dimensional or orthogonal cutting, rather than the usual three dimensional cutting. The basic principles apply in both situations; however, the two-dimensional model forms a clearer picture of the cutting situation.

"Orthogonal cutting is the case where the cutting tool generates a plane surface parallel to an original plane of the surface being cut and is set with its cutting edge perpendicular to the direction of relative motion of the tool and workpiece."[1] In orthogonal cutting there are two forces on the chip, the friction force(F) and the shear force (F_s) . The force diagram is as follows:



[1] Merchant, M. Eugene. "Mechanics of the Metal Cutting Process 1. Orthogonal Cutting and a Type 2 Chip," Journal of Applied Physics. Vol. 16, No. 5. May, 1945.

where:

F_s = shear force

F = friction force

F_n = normal force to the shear plane

N = normal force to the face of the tool

R = resultant of the forces F_s & F_n

R^1 = resultant of the forces F & N

ϕ = shear plane angle

α = back rake angle

τ = friction angle

t = depth of cut

t_c = thickness of the chip after cutting

F_c = vertical component of force

F_t = horizontal component of force

The vertical and horizontal components of force can be experimentally sensed with a two component dynamometer and recorded by a two channel strain amplifier recorder. Knowing F_c and F_t, and the back rake angle of the tool, the friction angle τ may be determined as follows:

$$F_t = F_c \tan\ (\tau - \alpha) \qquad \text{(fig 1)}$$

or

$$\tau = \tan^{-1} \frac{F_t}{F_c} + \alpha$$

In this method the forces (F_c and F_t) are found experimentally, and τ is determined from them.

However, the value of predicting the friction angle is in determining the forces present in the metal cutting operation, and not vice-versa. If the friction angle is dependent upon the cutting conditions, and a method can be developed to predict τ from these conditions, a more precise means of anticipating the requirements of the process is afforded.

If τ is known and the cutting ratio t/t_c is known, the forces can be determined in the following way:

$$r = t/t_c$$

$$\phi = \tan^{-1} \frac{r \cos \alpha}{1 - r \sin \alpha}$$

$$F_c = \frac{S_s \, A \, \mathrm{Cos}\,(\tau - \alpha)}{\sin \phi \, \mathrm{Cos}\,(\phi + \tau - \alpha)}$$

$$F_t = F_c \, (\tau - \alpha)$$

where S_s = shear stress of the material

A = feed x depth

α = back rake angle

Once the forces are known, power requirements can be determined. This knowledge will greatly aid the engineer in determining process capability, proper equipment and horsepower, and proper tooling.

Work in the Field

There are presently only three theories of any significance in the field: Ernst & Merchant (1941), Lee & Shaffer (1951), and Shaw, Cook, & Finnie (1952). All of these men were solving for the shear plane angle given the rake and friction angles. However, these equations are used to solve for the friction angle knowing the shear angle and the rake angle; and therefore should be discussed.

Ernst & Merchant

Ernst and Merchant assumed the shear stress on the shear plane to be uniformly distributed. They then assumed that the shear angle ϕ is the angle that maximized the shear stress. Their formula for the shear stress is:

$$S_s = \frac{F_s}{A} = \frac{R \cos(\phi + \tau - \alpha) \sin \phi}{A}$$

where: A = area of the shear plane (f x d)

ϕ = shear plane angle

α = rake angle

τ = friction angle

S_s = shear stress

Then differentiating this equation with respect to and equating to zero they obtained the relationship

$$\phi = 45 - \frac{\tau}{2} + \frac{\alpha}{2}$$

To get this relationship Ernst and Merchant made three assumptions:

1. That the shear stress is maximized in the direction of the shear plane.
2. That the friction angle is independent of the shear plane angle.
3. That the resultant force is independent of the shear plane angle.

All three of these assumptions have been questioned.

Shaw, Cook, and Finnie found that a tool operating with a fixed resultant force at an angle ($\tau-\alpha$) must have a shear plane at a fixed position which did not have to be in the direction of maximum shear stress. They also found that the friction angle is influenced by the shape of the stressed zone and therefore must be a function of the shear angle.

The third assumption was disproved by experimentation since the resultant force was dependent on the shear plane angle.[2]

Since this equation did not contain a term for the relationship of the normal stress to the shear stress, it was a poor approximation for polycrystalline materials.

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2 Shaw, M.C., N.H.Cook, and I. Finnie. "The Shear-angle Relationship in Metal Cutting," Transactions of the A.S.M.E., Vol. 75, No.2, pp. 273-279. February, 1953.

So Merchant developed a second equation:

$$2\Phi + \tau - \alpha = C$$

where C depends on the slope of the shear-strength vs. compressive - stress curve for the material.[3]

In the derivation of this equation the following assumptions were made:

1. That the shear angle is in the direction of minimum energy.
2. That the friction angle is independent of the shear plane angle.
3. That the shear stress on the shear plane is independent of the shear angle.

According to Hill the minimum energy theory does not always hold true. He states that "the comparative failure of this theory is almost certainly due to the inadequacy of the minimum-work hypothesis."[4]

The second assumption has been discussed earlier and the third assumption is roughly true.

In a study of Merchant's equation, R. Hill proved it incorrect due to the fact it was developed on a steady state condition and that the entire state of stress was not investigated. He showed a steady state condition could not exist except at the unique case when the rake

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[3] Black, Paul H. Theory of Metal Cutting. McGraw-Hill Book Company, Inc. New York, 1961, p.64.

[4] Shaw, M.C., N.H.Cook, and I.Finnie. "The Shear-angle Relationship in Metal Cutting," Transactions of the A.S.M.E. Vol. 75, No.2, p. 277, Feb. 1953.

angle was equal to the friction angle.[5]

Lee & Shaffer

Another approach to the solution of the force angles in cutting was made by Lee and Shaffer. They assumed that the material being cut acted as an ideal plastic with no strain hardening and that the shear plane was in the direction of maximum shear stress. Since the region ahead of the tool must be rigid and subject to a uniform stress field, the stress at any point could be represented by a Mohr's-circle diagram. From the diagram they developed the equation:

$$\phi = 45 + \alpha - \tau$$

The assumption that the material acts as an ideal plastic is not the usual case. In this condition, the shear stress and the normal stress on the shear plane would be equal. This is not generally true. Also, nearly all metals that are machined become strain hardened as they are being cut, and therefore will not act as an ideal plastic.

Since this equation did not agree favorably with experimental results, Lee and Shaffer then considered the effect of a built-up edge on the stress field, and

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5 Hill, R. "The Mechanics of Machining: A New Approach," Journal of the Mechanics and Physics of Solids. Vol. 3, No. 10, pp.47-53. October, 1954.

arrived at the following expression:

$$\phi = 45 + \theta - \tau + \alpha$$

σ = normal stress

where

t = shear stress

$$\theta = \frac{\frac{\sigma}{t} - 1}{2}$$

However the equation is still built upon the ideal plastic concept.

Hill also disproved the solution of Lee and Shaffer. He examined in detail the permissible singularities of stress in an ideal plastic rigid material. At each end of the shear plane stress singularities are present. There is only a small range of values where there will not be overstressed material at a singularity. Lee and Shaffer state that the angle between the shear plane and the tool face must not be less than $\frac{1}{4}\pi + \tau$, but their proof is invalid since they do not allow for a possibility of a stress singularity.[6]

Shaw, Cook, and Finnie

Shaw, Cook and Finnie studied the past work and extended the theory on angle relationships. They concluded:

"1. Friction encountered in the cutting process is basically different from that for ordinary sliding contacts, owing to a variation of the effective indentation hardness of the metal

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6 ibid p. 48-49.

at the point of the tool under different cutting conditions.

2. There is a significant interrelationship between the shear and friction processes in cutting brought about by the close proximity of the processes and the fact that they are connected by a common stress field.
3. The effective hardness of the chip metal increases as a result of the increased restraint associated with a decrease in the angle between shear plane and tool face.
4. The effective hardness of the chip thus increases with a decrease in rake angle, which in turn gives rise to a significant decrease in the coefficient of friction with decreased rake angle.
5. The interconnection between the shear and friction processes prevents the shear plane from being in the direction of maximum shear stress in the general case.
6. The assumption of a uniform state of stress in the vicinity of the tool point is a good first assumption.
7. Applying the concepts expressed in items 5 and 6, it is found that the shear angle is given

at the point of the tool under different cutting conditions.

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6. The assumption of a uniform state of stress in the vicinity of the tool point is a good first assumption.
7. Applying the concepts expressed in items 5 and 6, it is found that the shear angle is given

by

$$\Phi = 45 + N^1 - \tau + \alpha$$

where N^1 is the angle between the shear plane and the direction of maximum shear stress.

8. It is found experimentally that N^1 may be either positive or negative."[7]

The validity of the results of these men also have been questioned. E.H.Lee makes the following comments:

"1. In particular, the results from this equation are far away from Merchant's often quoted experimental results which have been confirmed by other workers.

2. In all previously published work only positive N^1's have been reported.

3. The assumption that the shear plane behaves as a rigid restraining surface seems open to question since the material below it has not been strained appreciably and so may be softer and provide less restraint rather than more."[8]

In conclusion of this section, I would like to quote Paul H. Black:

> "Since no single criterion is applicable to the angle relationship in metal cutting, and since a satisfactory theory has not been advanced at present to explain the experimental observations

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[7] Shaw, M.C., N.H.Cook, and I. Finnie. "The Shear-angle Relationship in Metal Cutting," Transactions of the A.S.M.E. Vol. 75, No. 2, p. 282.

[8] ibid p. 285.

adequately, the challenge exists for a closer solution to the problem of angle relationships."[9]

[9] Black, Paul H. Theory of Metal Cutting. McGraw-Hill Book Company, Inc. New York, 1961. p.64.

Analysis of the Friction Angle

This study dealt with the effect of the cutting conditions on the friction angle. The conditions that varied were feed, depth, work material, and back rake angle. Four feeds (.0051, .0102, .0204, .0410 in/rev.) were run at four depths (.010, .020, .040, .080 in.) with two rake angles (-5°, +6°) on two materials (1020 HRS, 4340 HRS). Two data points were taken for each condition. The secuence used in the experiment and the data recorded is in Appendix A.

The cutting conditions that were kept constant were speed and tool material. Over the normal range of speeds for carbides, the speed has very little effect on the cutting forces. O.W.Boston determined equations for the magnitude of the forces based on functions of the feed and the depth. He said, "These forces are independent of speed."[10] The experiment was run at a speed of 450 SFPM .

The tool material was carbide of Carboloy grade 350. The results should hold true for all grades of carbides although very little investigation has been done in this area.

The experiment was run on a 20 HP engine lathe and the vertical force (F_c) and the horizontal force (F_t) were

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10 Boston, O.W. Metal Processing. John Wiley & Sons, Inc. New York, 1958. p. 165.

sensed with a two component dynamometer and recorded by a two channel strain amplifier-recorder. The forces recorded are in Appendix A. From these forces the friction angle (τ) was calculated.

$$F_t = F_c \tan(\tau - \alpha)$$

or

$$\tau = \alpha + \tan^{-1} \frac{F_t}{F_c}$$

The calculated values of τ are in Appendix A.

Analysis of Variance

The next step was to test the significance of the variables with an analysis of variance. Using a 95% confidence level, all the variables and their interactions were significant, except for the rake angle being affected by material. (See Appendix B for the results of the Analysis of Variance).

After finding the variables significant, the next step was to develop an equation to predict the friction angle. To determine the important terms and to keep the equation as simple as possible, the highly significant terms of the analysis of variance were regrouped and the other terms were placed in the residual term. (See Appendix B).

The significant terms were:

1. material
2. rake angle
3. depth

4. feed
5. interaction of depth and feed
6. interaction of material and feed
7. interaction of material and depth
8. interaction of material, feed, and depth

If a single equation were to be developed it would have to include all of these terms. However, if the equation were written for a material or type of material all the interaction terms including material would be eliminated. This would yield an equation containing the following functions:

$$\tau = a + b_1 f(\text{depth}) + b_2 f(\text{feed}) + b_3 f(\text{feed x depth}) + b_4 f(\text{rake angle})$$

Regression Analysis

To determine what the functions should be in the equation for predicting the friction angle, their effects were graphed. For example, to find the effect of depth of cut on τ, the sums and averages of the values of τ at each depth for a given rake angle and material were plotted. The effect of feed was determined in a similar manner. (See Appendix C.)

The shape of these curves seemed to follow a log function. One graph of feed and depth was selected at random and plotted on a semi-log paper. These points fell in a straight line. (Appendix C).

Looking at the original graphs in detail showed that the rake angle had a constant effect on the friction angle. The equation was then solved for the constants using the LGP 30. The Regression Analysis for this solution is shown in Appendix D. The equations developed are as follows:

[illegible] material

$$\tau = -4.4 + 27.8\log f - 6.0\log d - 6.2\log f \log d + .48$$

4340 material

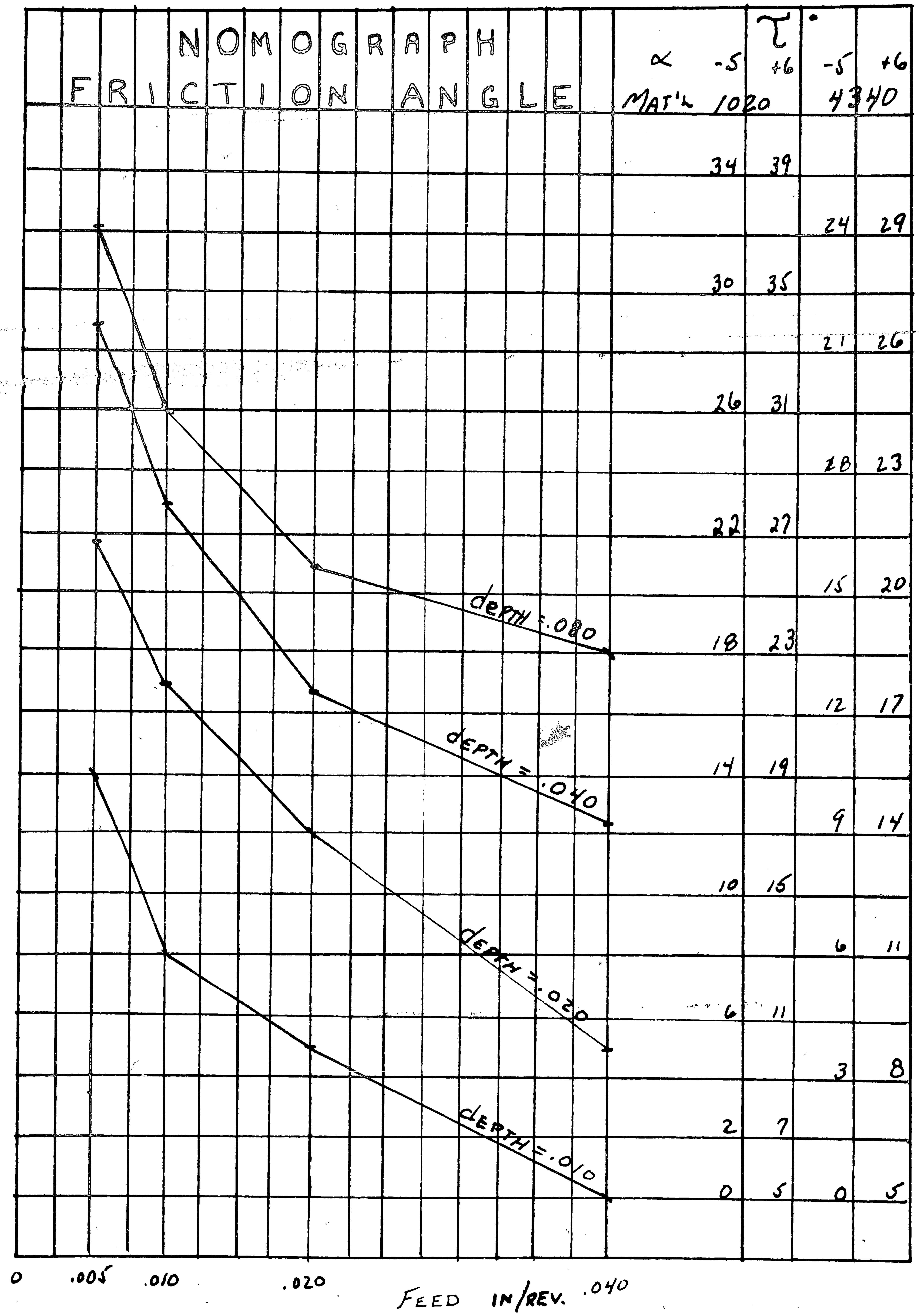
$$\tau = 22.2 + 5.2\log f - 23.0\log d + 7.0\log f \log d + .45$$

where f = feed x 1000
d = depth x 1000
α = back rake angle

A comparison of the experimental τ's and the predicted τ's are shown in Appendix D under the heading y and exp y.

Nomograph

A nomograph was also developed to predict τ . This graph will give a quick and easy prediction of τ . (See next page.) The accuracy of the nomograph is approximately $\pm$ 2 degrees. With finishing cuts it is not as accurate as it is with larger feeds and depths. Since force relationships are more critical in roughing operations, the nomograph in this area will act as an excellent predictor of the friction angle.


NOMOGRAPH
FRICTION ANGLE
α
τ
-5
+6
-5
+6
MAT'L
1020
4340
34 39
24 29
30 35
21 26
26 31
18 23
22 27
15 20
18 23
12 17
14 19
9 14
10 15
6 11
6 11
3 8
2 7
0 5 0 5
depth = .080
depth = .040
depth = .020
depth = .010
0
.005
.010
.020
.040
FEED IN/REV.

Results and Conclusions

The formulas developed to predict (τ) were:

1020 HRS

$$\tau = -4.4 + 27.8 \log f - 6.0 \log d - 6.2 \log f \log d + .48\alpha$$

4340 HRS

$$\tau = 22.2 + 5.2 \log f - 23.0 \log d + 7.0 \log f \log d + .45\alpha$$

where f is feed(in/rev) x 1000, d is depth(in.) x 1000, and α is the back rake angle(degrees). This method will yield a value for (τ) within 3°, 95 % of the time.

The following conclusions were drawn from this study:

(1) The present angle relationships in metal cutting are inadequate.

(2) The friction angle (τ) is dependent on the cutting conditions.

(3) The significant variables are the work material, depth, feed, and back rake angle.

(4) Formulas can be derived to predict the friction angle. (See above).

(5) If a similar study is sucessfully made to predict the shear plane angle (ϕ) from the cutting conditions, and is then coupled with (τ) from this study; the magnitude and direction of the cutting forces will be known without taking an experimental cut. This knowledge will greatly aid the engineer in determining process capability, proper equipment and horsepower, and proper tooling.

Areas for Future Study

This study revealed the following areas for future work:

1. The effect of work material on the friction angle (τ). The equations and nomograph developed differ by work material. The reasons for this difference would lead toward a fruitful area for future study.
2. The effect of cutting conditions on the shear plane angle (ϕ). The prediction of (ϕ) from the cutting conditions, coupled with (τ) from this study, would allow the magnitude and direction of the cutting forces to be known without taking an experimental cut.
3. The effect of tool wear on the friction angle and the shear plane angle. As a tool wears the angle relationships change. These changes have an effect on the forces. If these changes could be predicted, the force relationships over the entire life of the tool could be studied to determine optimum cutting conditions.

Appendix A

Appendix A

Data

Due to set-up difficulties the data was not taken in a random order point by point. The first data point at each condition was taken in a logical order chosen by the author. However the second data point at each condition was taken randomly by rake angle and depth of cut, given the material. The feed was then varied at that depth of cut. The reasons for not varying randomly point to point are:

(1) Impractical to change work material back and forth.

(2) Setting the tool in the dynamometer is critical for proper force readings and therefore once it is set for a depth of cut all feeds at that depth should be run.

Here is the order in which the data was taken:

	Material	Rake Angle	Depth	Feed
1.	1020	+6	.080	.0051
2.	1020	+6	.080	.0102
3.	1020	+6	.080	.0204
4.	1020	+6	.080	.0410
5.	1020	+6	.040	.0051
6.	1020	+6	.040	.0102
7.	1020	+6	.040	.0204
8.	1020	+6	.040	.0410
9.	1020	+6	.020	.0051
10.	1020	+6	.020	.0102
11.	1020	+6	.020	.0204
12.	1020	+6	.020	.0410
13.	1020	+6	.010	.0051
14.	1020	+6	.010	.0102
15.	1020	+6	.010	.0204
16.	1020	+6	.010	.0410
17.	1020	-5	.080	.0051
18.	1020	-5	.080	.0102
19.	1020	-5	.080	.0204
20.	1020	-5	.080	.0410
21.	1020	-5	.040	.0051
22.	1020	-5	.040	.0102
23.	1020	-5	.040	.0204
24.	1020	-5	.040	.0410
25.	1020	-5	.020	.0051
26.	1020	-5	.020	.0102
27.	1020	-5	.020	.0204
28.	1020	-5	.020	.0410
29.	1020	-5	.010	.0051
30.	1020	-5	.010	.0102
31.	1020	-5	.010	.0204
32.	1020	-5	.010	.0410

	Material	Rake Angle	Depth	Feed
33.	1020	-5	.040	.0410
34.	1020	-5	.040	.0204
35.	1020	-5	.040	.0102
36.	1020	-5	.040	.0051
37.	1020	+6	.040	.0410
38.	1020	+6	.040	.0204
39.	1020	+6	.040	.0102
40.	1020	+6	.040	.0051
41.	1020	+6	.080	.0410
42.	1020	+6	.080	.0204
43.	1020	+6	.080	.0102
44.	1020	+6	.080	.0051
45.	1020	+6	.010	.0410
46.	1020	+6	.010	.0204
47.	1020	+6	.010	.0102
48.	1020	+6	.010	.0051
49.	1020	+6	.020	.0410
50.	1020	+6	.020	.0204
51.	1020	+6	.020	.0102
52.	1020	+6	.020	.0051
53.	1020	+6	.020	.0410
54.	1020	+6	.020	.0204
55.	1020	+6	.020	.0102
56.	1020	+6	.020	.0051
57.	1020	-5	.010	.0410
58.	1020	-5	.010	.0204
59.	1020	-5	.010	.0102
60.	1020	-5	.010	.0051
61.	1020	-5	.080	.0410
62	1020	-5	.080	.0204
63.	1020	-5	.080	.0102
64.	1020	-5	.080	.0051

	Material	Rake Angle	Depth	Feed
65.	4340	+6	.080	.0051
66.	4340	+6	.080	.0102
67.	4340	+6	.080	.0204
68.	4340	+6	.080	.0410
69.	4340	+6	.040	.0051
70.	4340	+6	.040	.0102
71.	4340	+6	.040	.0204
72.	4340	+6	.040	.0410
73.	4340	+6	.020	.0051
74.	4340	+6	.020	.0102
75.	4340	+6	.020	.0204
76.	4340	+6	.020	.0410
77.	4340	+6	.010	.0051
78.	4340	+6	.010	.0102
79.	4340	+6	.010	.0204
80.	4340	+6	.010	.0410
81.	4340	-5	.080	.0051
82.	4340	-5	.080	.0102
83.	4340	-5	.080	.0204
84.	4340	-5	.080	.0410
85.	4340	-5	.040	.0051
86.	4340	-5	.040	.0102
87.	4340	-5	.040	.0204
88.	4340	-5	.040	.0410
89.	4340	-5	.020	.0051
90.	4340	-5	.020	.0102
91.	4340	-5	.020	.0204
92.	4340	-5	.020	.0410
93.	4340	-5	.010	.0051
94	4340	-5	.010	.0102
95.	4340	-5	.010	.0204
96.	4340	-5	.010	.0410

	Material	Rake Angle	Depth	Feed
97.	4340	-5	.020	.0410
98.	4340	-5	.020	.0204
99.	4340	-5	.020	.0102
100.	4340	-5	.020	.0051
101.	4340	+6	.080	.0410
102.	4340	+6	.080	.0204
103.	4340	+6	.080	.0102
104.	4340	+6	.080	.0051
105.	4340	+6	.010	.0410
106.	4340	+6	.010	.0204
107.	4340	+6	.010	.0102
108.	4340	+6	.010	.0051
109.	4340	-5	.080	.0410
110.	4340	-5	.080	.0204
111.	4340	-5	.080	.0102
112.	4340	-5	.080	.0051
113.	4340	+6	.040	.0410
114.	4340	+6	.040	.0204
115.	4340	+6	.040	.0102
116.	4340	+6	.040	.0051
117.	4340	-5	.040	.0410
118.	4340	-5	.040	.0204
119.	4340	-5	.040	.0102
120.	4340	-5	.040	.0051
121.	4340	-5	.010	.0410
122.	4340	-5	.010	.0204
123.	4340	-5	.010	.0102
124.	4340	-5	.010	.0051
125.	4340	+6	.020	.0410
126.	4340	+6	.020	.0204
127.	4340	+6	.020	.0102
128.	4340	+6	.020	.0051

Material 1020 Hot Rolled Steel

Negative Rake Angle

	Fc	(lbs)		Ft		τ (degrees) τ	
d=.080	1	2	1	2	1	2	Ave
f=.0051	180	195	133	150	31.5	32.6	32.0
f=.0102	295	360	177	200	26.0	24.1	25.0
f=.0204	500	528	235	262	20.2	20.5	20.3
f=.041	1025	970	450	440	19.4	18.7	19.0
d=.040							
f=.0051	100	120	71	90	30.2	31.8	31.0
f=.0102	152	155	85	85	24.1	23.8	24.0
f=.0204	286	275	120	120	17.8	18.6	18.2
f=.041	467	440	140	130	11.8	11.5	11.6
d=.020							
f=.0051	49	45	20	20	17.2	19.0	18.1
f=.0102	80	80	30	30	15.6	15.7	15.6
f=.0204	158	135	50	45	12.5	13.3	12.9
f=.0410	225	210	35	35	4.5	3.8	4.1
d=.010							
f=.0051	27	30	9	10	13.4	13.4	13.4
f=.0102	40	40	40	10	9.0	9.0	9.0
f=.0204	72	68	12	11	4.5	4.0	4.2
f=.0410	99	12[illegible]	5	7	-1.8	-1.8	-1.8

Material 1020 Hot Rolled Steel

Positive Rake Angle

	Fc (lbs)		Ft		τ (degrees) τ		
d=.080	1	2	1	2	1	2	Ave
f=.0051	145	138	90	82	37.8	36.8	37.3
f=.0102	230	220	125	105	34.5	31.6	33.0
f=.0204	340	380	140	130	38.6	25.0	26.8
f=.041	710	697	200	196	21.7	21.7	21.7
d=.040							
f=.0051	75	77	37	37	32.3	31.7	32.0
f=.0102	130	140	59	60	30.4	29.3	29.8
f=.0204	223	225	67	68	22.7	22.8	22.7
f=.041	390	405	78	80	17.3	17.2	17.3
d=.020							
f=.0051	34	36	10	10	22.4	21.5	21.9
f=.0102	65	71	20	21	24.1	23.2	23.6
f=.0204	125	120	28	25	18.6	17.8	18.2
f=.0410	225	220	22	23	11.6	11.9	11.8
d=.010							
f=.0051	20	16	3	2	14.5	13.5	14.1
f=.0102	36	32	5	7	13.9	10.5	12.2
f=.0204	57	58	8	7	12.8	10.9	11.9
f=.0410	130	113	2	3	6.9	7.6	7.2

Material 4340 Hot Rolled Steel

Negative Rake Angle

	Fc (lbs) 1	Fc (lbs) 2	Ft 1	Ft 2	τ (degrees) 1	τ (degrees) 2	τ Ave
d=.080							
f=.0051	180	179	100	102	24.0	24.7	24.3
f=.0102	300	305	130	142	18.4	19.5	19.0
f=.0204	550	540	220	230	16.8	18.2	17.5
f=.041	x	x	x	x	15.0	15.0	15.0
d=.040							
f=.0051	90	90	46	45	22.0	21.6	21.8
f=.0102	160	155	60	60	15.5	16.1	15.8
f=.0204	286	270	92	80	12.9	11.5	12.2
f=.0410	520	500	170	150	13.1	11.7	12.4
d=.020							
f=.0051	42	52	18	22	18.2	18.0	18.1
f=.0102	80	83	25	27	12.3	13.0	12.7
f=.0204	160	130	40	30	9.0	8.0	8.5
f=.0410	257	220	38	31	3.4	3.0	3.2
d=.010							
f=.0051	28	35	9	11	12.8	12.4	12.6
f=.0102	36	42	7	9	6.0	7.1	6.5
f=.0204	61	75	9	10	3.4	2.6	3.0
f=.0410	142	119	11	10	-.5	-.2	-.3

Material 4340 Hot Rolled Steel

Positive Rake Angle

	Fc (lbs)		Ft		τ(degrees)		
d=.080	1	2	1	2	1	2	Ave
f=.0051	160	160	63	69	27.5	29.3	28.4
f=.0102	273	272	82	80	22.7	22.4	22.5
f=.0204	510	481	151	128	22.5	20.9	21.7
f=.041	x	x	x	x	19.0	19.0	19.0
d=.040							
f=.0051	85	80	30	30	25.5	26.6	26.0
f=.0102	143	140	30	35	17.9	19.7	18.8
f=.0204	250	250	44	40	16.0	15.1	15.5
f=.0410	450	490	90	90	17.3	16.4	16.8
d=.020							
f=.0051	46	47	13	15	21.8	23.7	22.7
f=.0102	77	79	17	18	18.5	18.8	18.6
f=.0204	136	132	12	17	11.1	13.3	12.2
f=.0410	240	236	7	10	7.7	8.4	8.0
d=.010							
f=.0051	28	29	6	7	19.5	18.1	18.8
f=.0102	43	45	8	9	17.3	16.6	17.0
f=.0204	72	72	4	4	9.2	9.2	9.2
f=.0410	120	130	0	0	6.0	6.0	6.0

Data Sheet

Variables

1. Feed (4) .0051, .0102, .0204, .0410 in/rev.

2. Depth (4) .010, .020, .030, .040 in.

3. Tool Geometry (2) +6, -5 back rake angle

4. Work Material (2) 1020 HRS, 137 bhn, 94,500 S_s
   6.326 diam.

   4340 HRS, 300 bhn, 130,300 S_s
   6.195 diam.

Constants

1. Speed - 450 SFPM

2. Tool Material - Carboloy Grade 350

3. Tool Geometry - Insert TBT 163 P3, TBP163 P3
   Tool Holders - T6TR - 16, TGPR - 85

Equipment

1. 20 HP Le Blond Engine Lathe

2. 2 Component Dynamometer

3. Strain Amplifier Recorder

4. LGP - 30 Computer

5. Vari-Dyne Speed Control

Appendix B

Analysis of Variance

The analysis of variance was run on the LGP-30 computer. The coding was as follows:

Source	- the variables
df	- degrees of freedom
ss	- sum of squares
ms	- mean square
a	- material
b	- rake angle
c	- depth of cut
d	- feed rate

In order to run the analysis of variance all data conditions needed a value. Since there were four points unattainable in experimentation it was necessary to approximate these points. In doing this four degrees of freedom were relinquished from the residual term abcde.

This first analysis of variance is straight from the computer using all the terms, and the second is regrouped into highly significant terms with the residual containing the other terms.

Analysis of Variance I.

source	df	ss	ms
+ a	1.	41148.	41148.
+ b	1.	83896.	83896.
+ c	3.	419854.	139951.
+ d.	3.	282881.	94293.
ab	1.	90.	90.
+ ac	3.	21653.	7217.
ad	3.	6639.	2213.
+ bc	3.	2122.	707.
bd	3.	2343.	781.
+ cd	9.	7312.	812.
abc	3.	1819.	606.
abd	3.	1723.	574.
acd	9.	13728.	1525.
bcd	9.	2235.	248.
abcd	9.	4201.	466.
abcde	64.	4585.	71.
Total	127.	896229.	
$\sum x$	21645.		

Analysis of Variance 2

source	df	ss	ms
a	1	41148	41148
b	1	83896	83896
c	3	419854	139951
d	3	282881	94293
ac	3	21653	7217
ad	3	6639	2213
cd	9	7312	812
acd	9	13728	1525
residual	95	19117	201

F Table

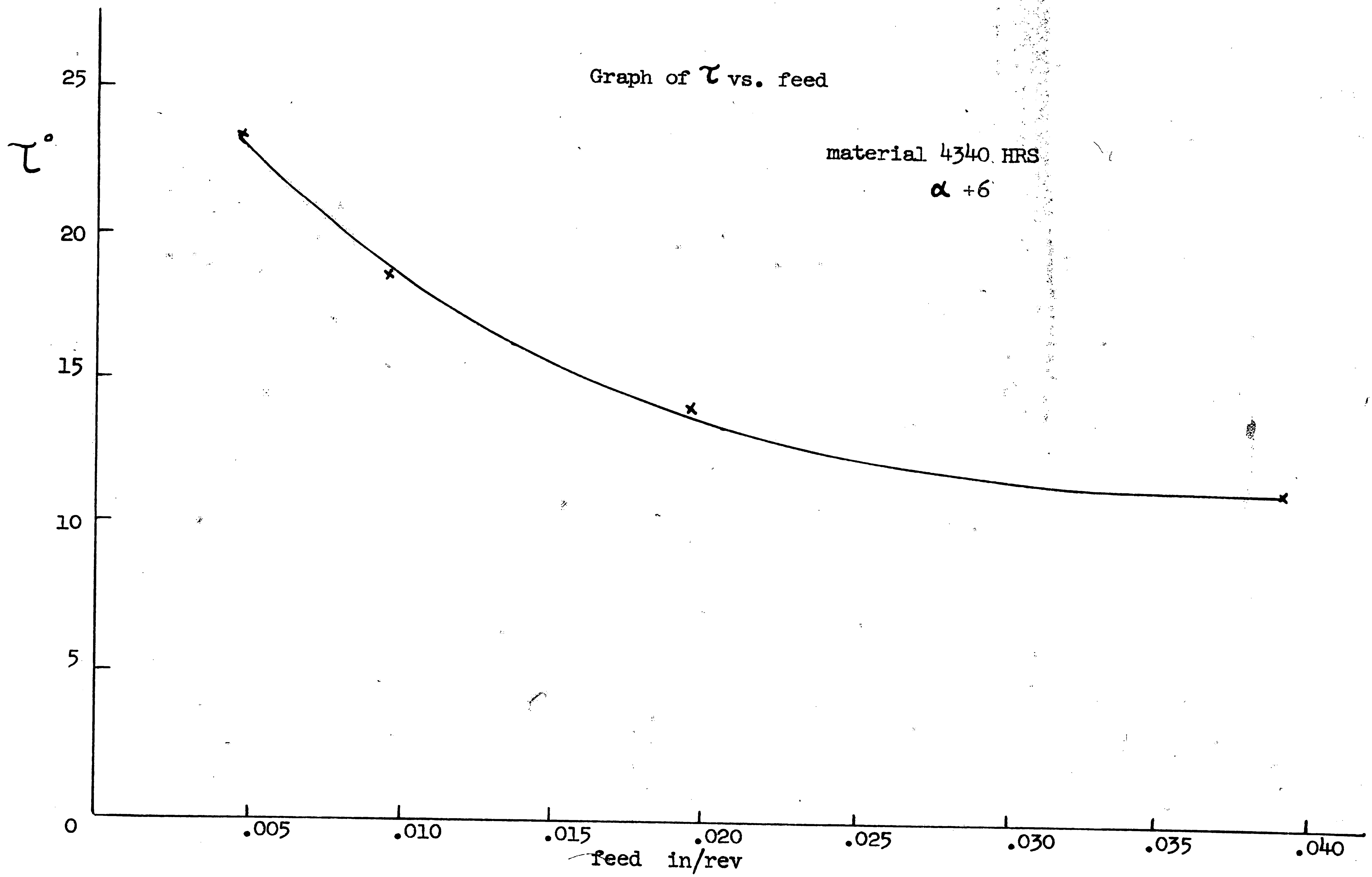
.95 - confidence level

m - degrees of freedom in numerator

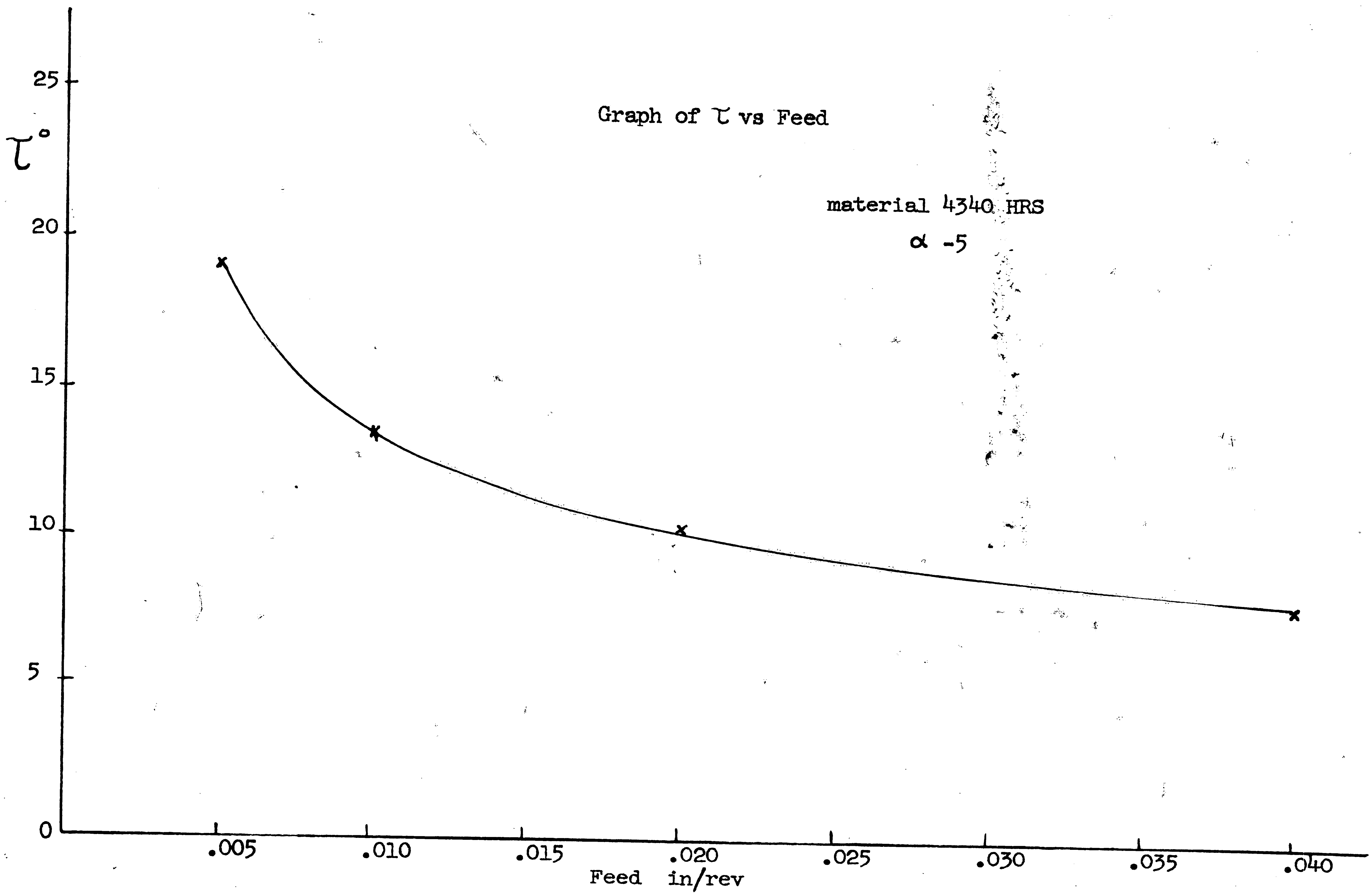
n = degrees of freedom in denominator

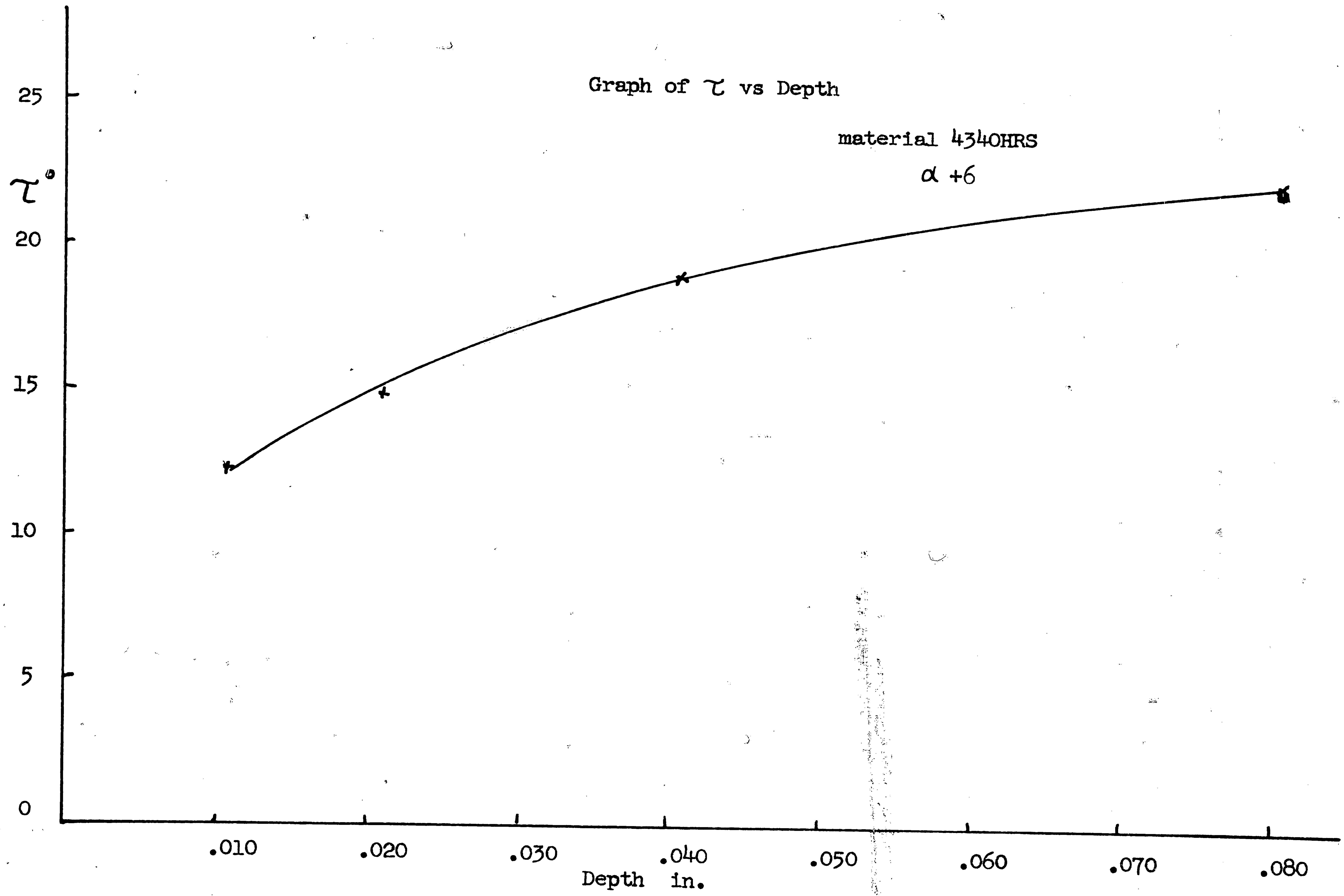
m	1	3	9
n			
9	5.12	3.86	3.18
60	4.00	2.76	2.04
120	3.92	2.68	1.96

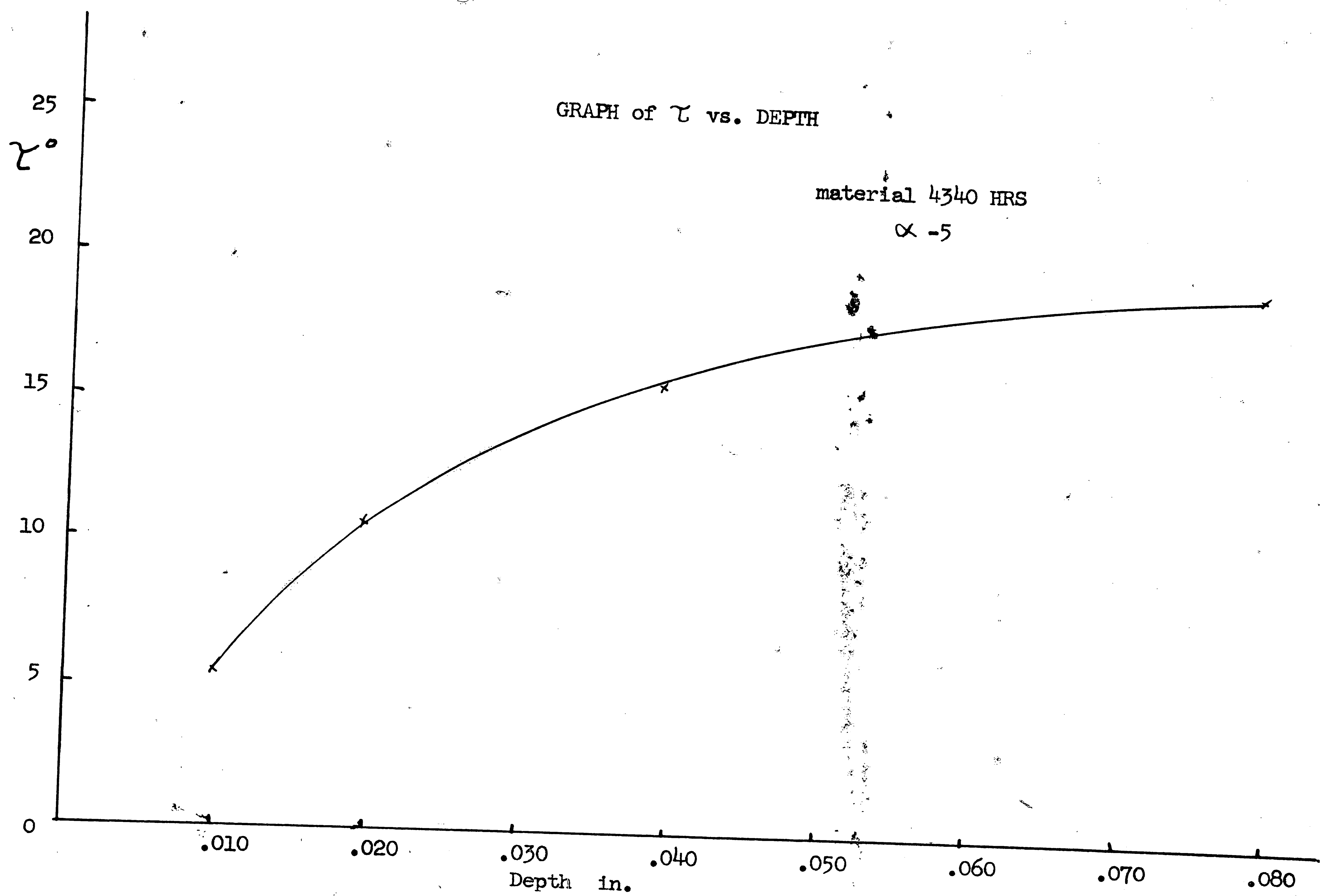
Appendix C

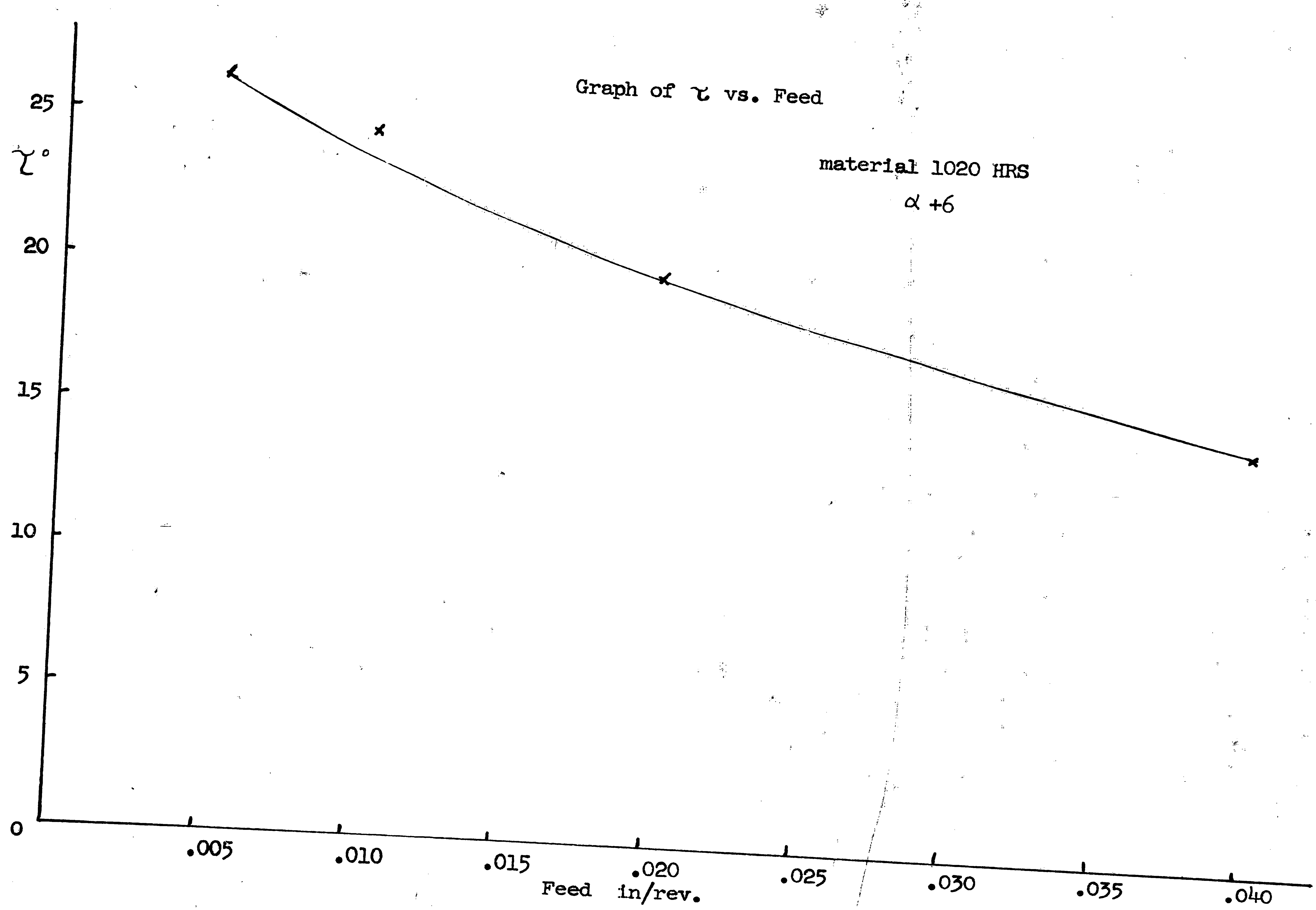


Graph of τ vs. feed
material 4340 HRS
α +6
τ°
25
20
15
10
5
0
.005
.010
.015
.020
.025
.030
.035
.040
feed in/rev

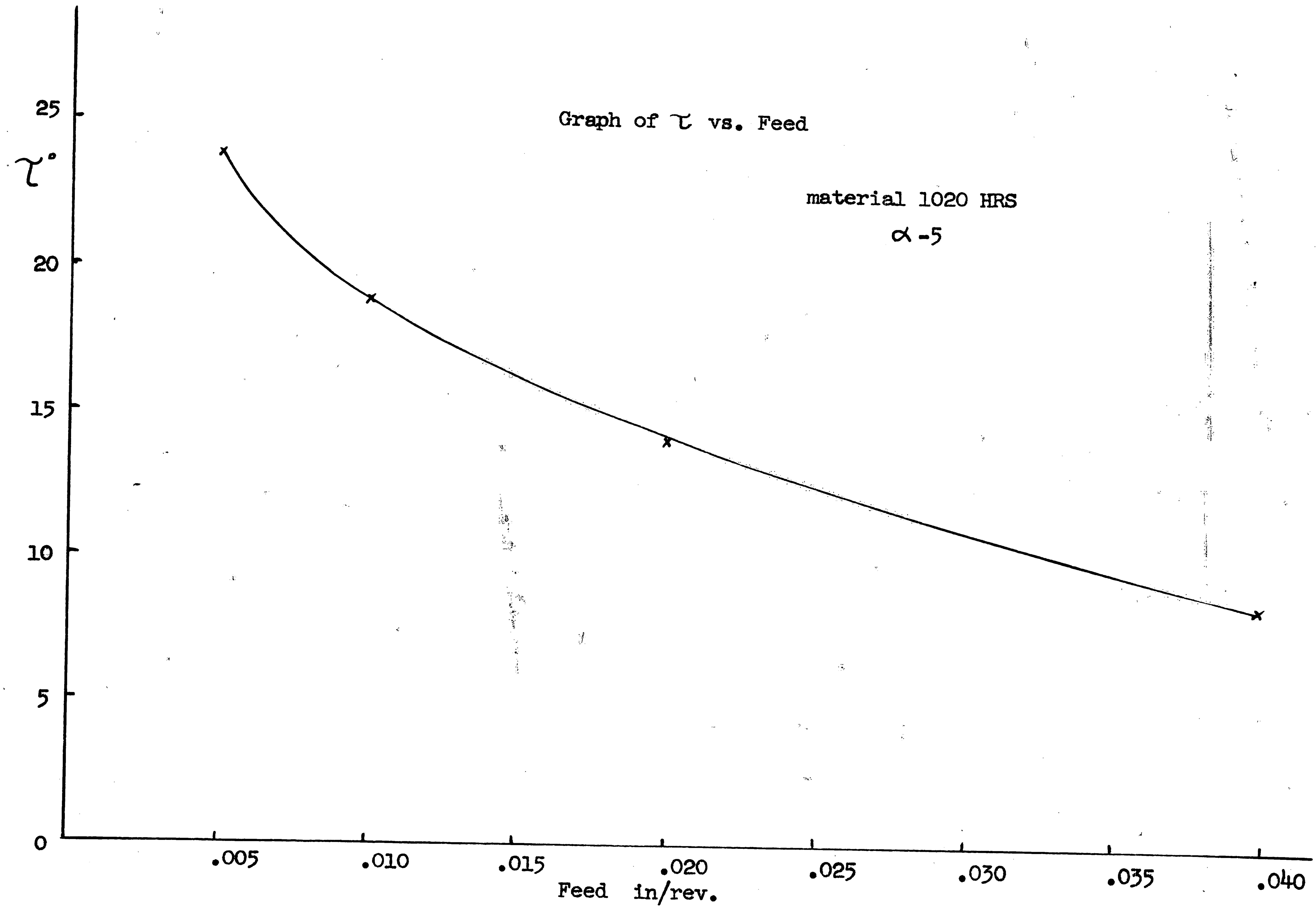

Graph of τ vs Feed
material 4340 HRS
α -5
τ°
25
20
15
10
5
0
.005
.010
.015
.020
.025
.030
.035
.040
Feed in/rev

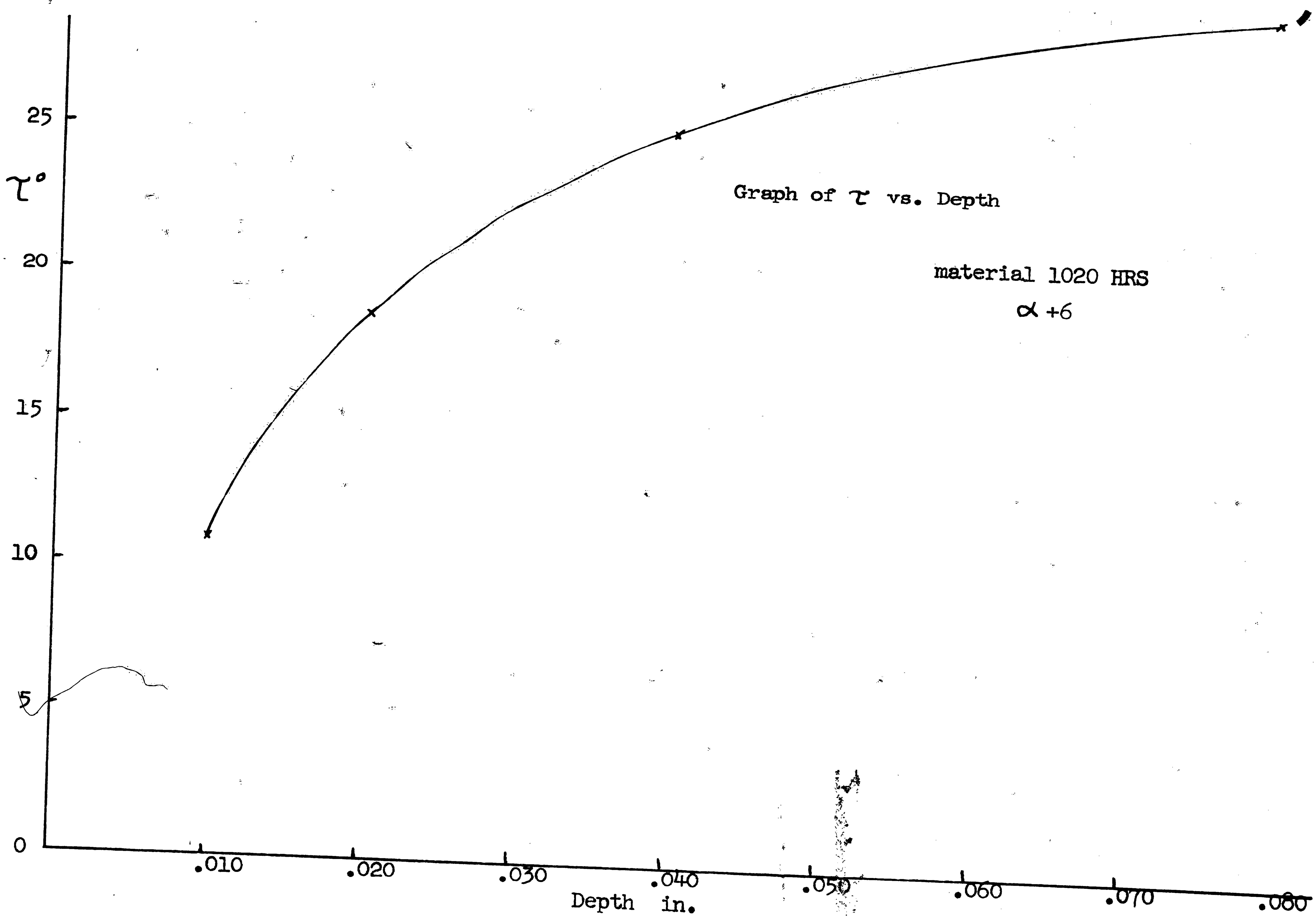

Graph of τ vs Depth
material 4340HRS
α +6
τ°
25
20
15
10
5
0
.010
.020
.030
.040
.050
.060
.070
.080
Depth in.


GRAPH of τ vs. DEPTH
material 4340 HRS
α -5
τ°
25
20
15
10
5
0
.010
.020
.030
.040
.050
.060
.070
.080
Depth in.
40.

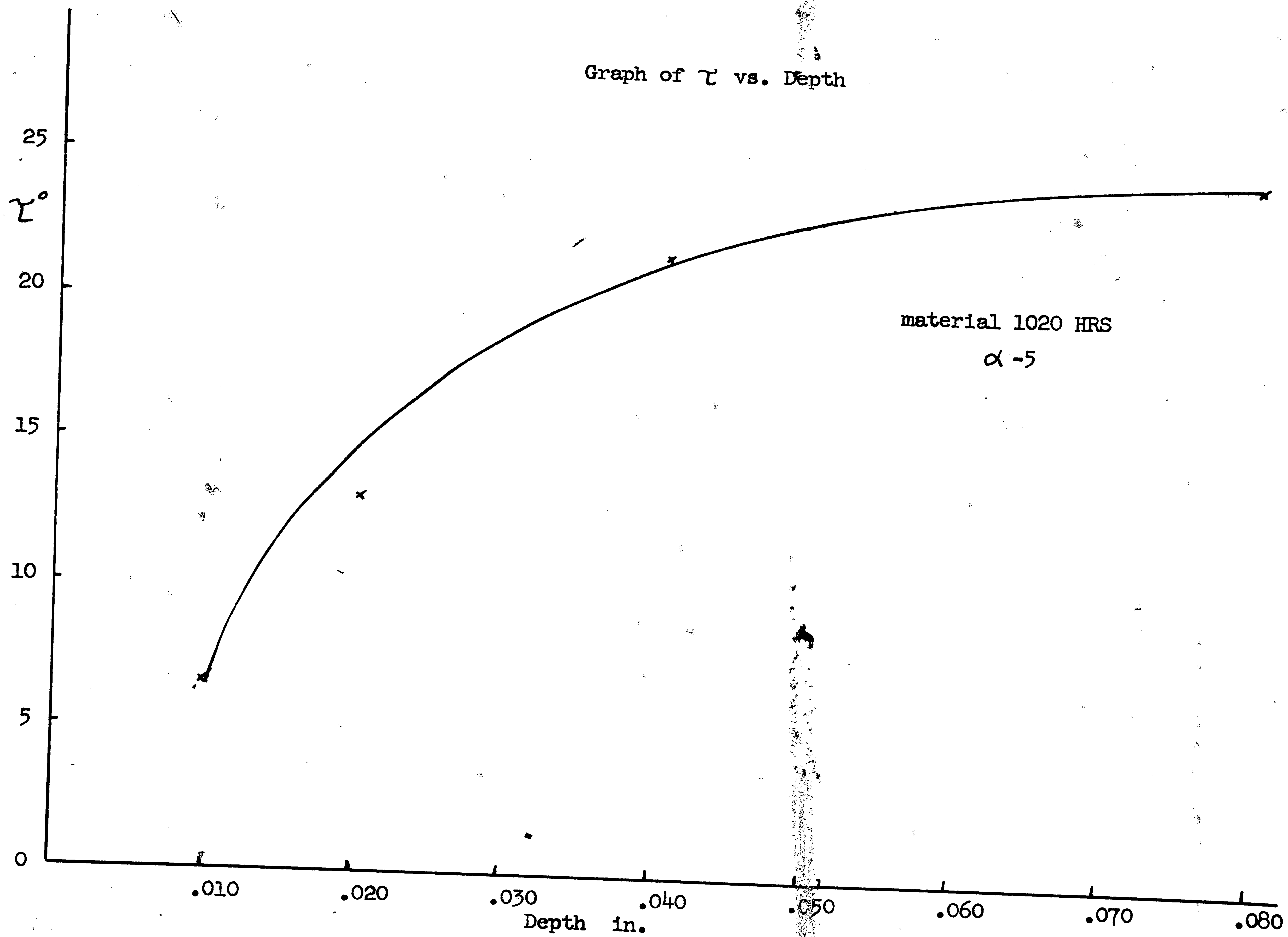


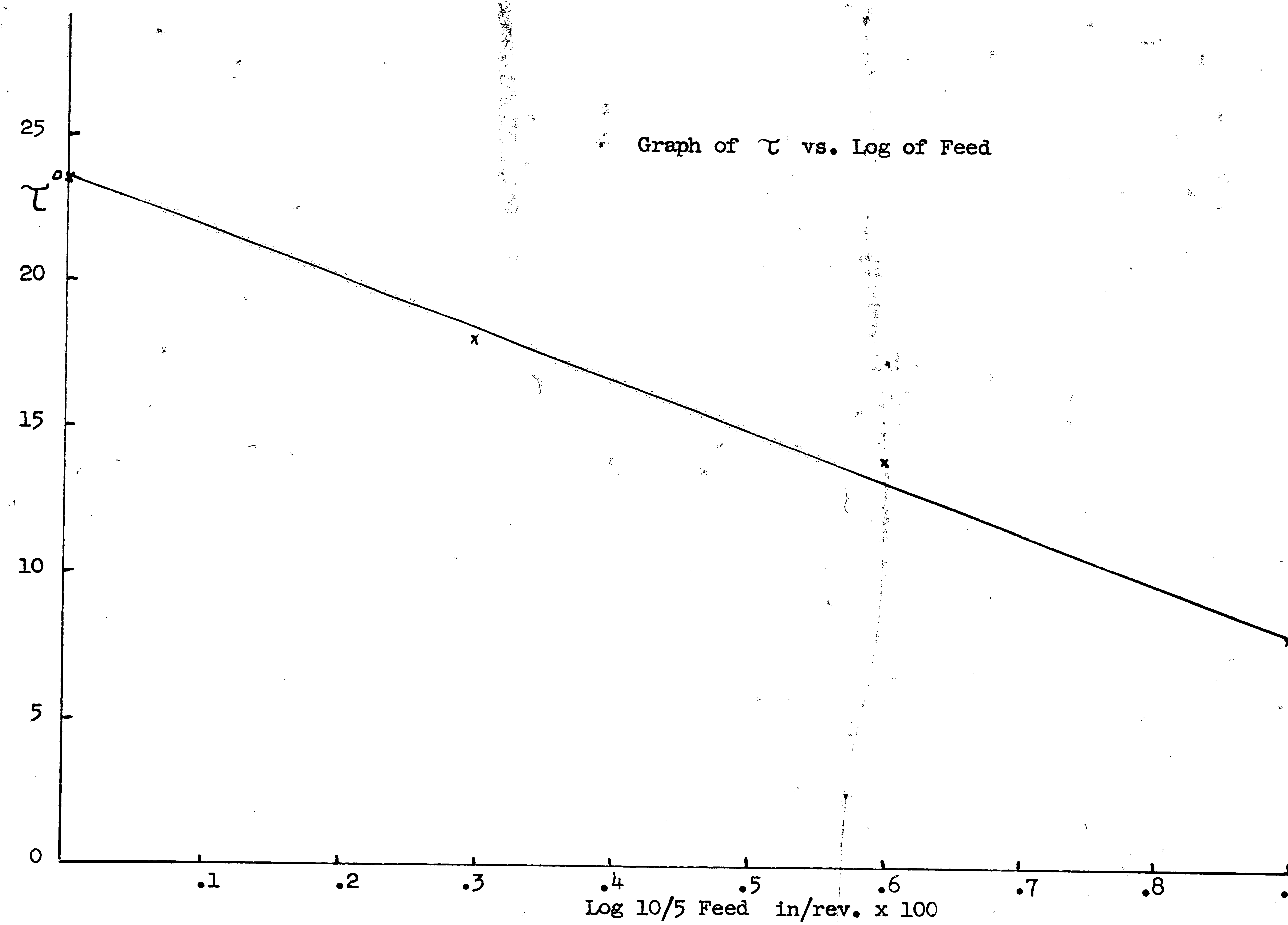
Graph of τ vs. Feed
material 1020 HRS
α +6
τ°
25
20
15
10
5
0
.005
.010
.015
.020
.025
.030
.035
.040
Feed in/rev.

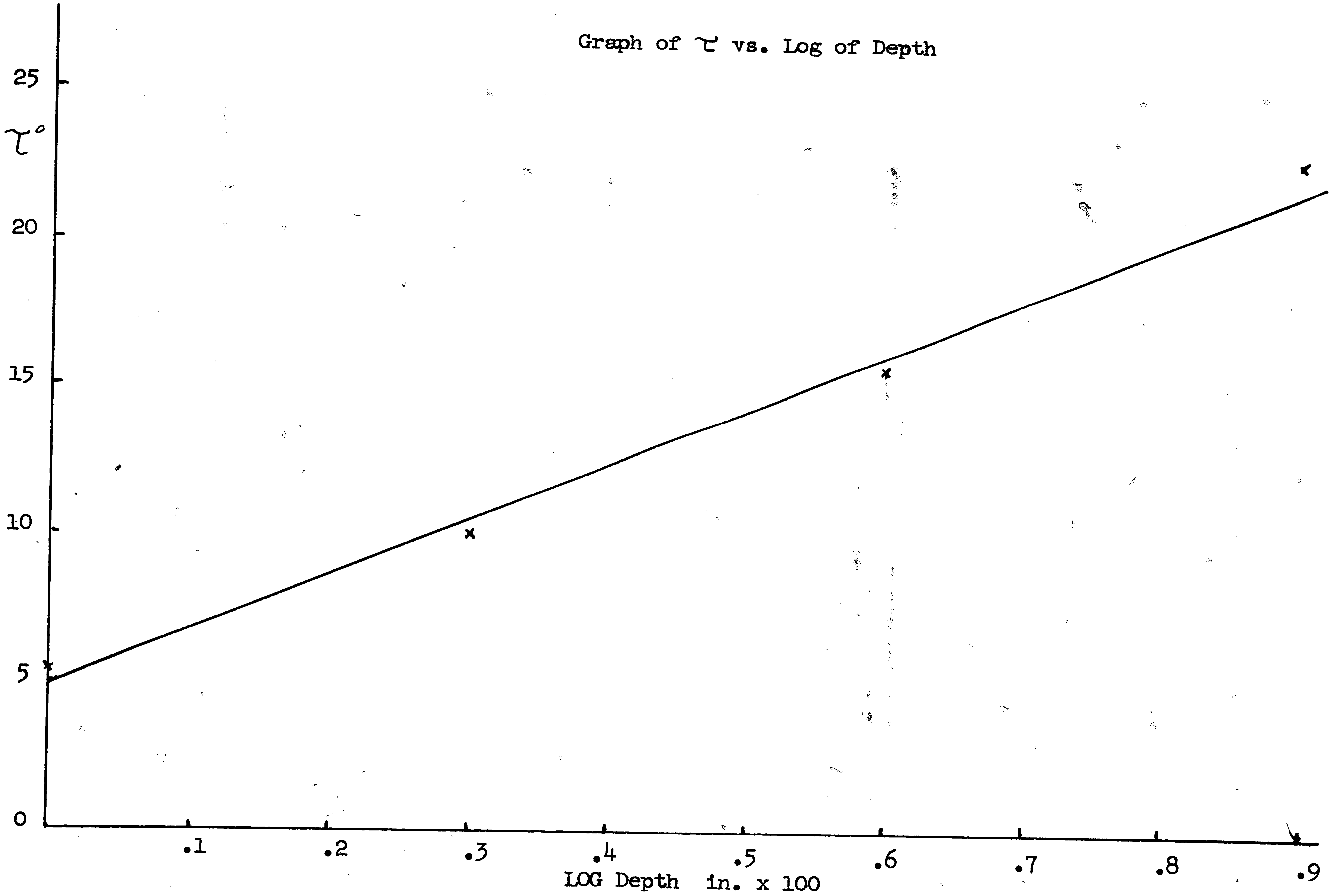

Graph of τ vs. Feed
material 1020 HRS
α -5
τ°
25
20
15
10
5
0
.005
.010
.015
.020
.025
.030
.035
.040
Feed in/rev.



Graph of τ vs. Depth
material 1020 HRS
α +6
τ°
25
20
15
10
5
0
.010
.020
.030
.040
.050
.060
.070
.080
Depth in.


Graph of τ vs. Depth
25
τ°
20
15
10
5
0
material 1020 HRS
α -5
.010
.020
.030
.040
.050
.060
.070
.080
Depth in.


Graph of τ vs. Log of Feed
τ°
25
20
15
10
5
0
.1
.2
.3
.4
.5
.6
.7
.8
.9
Log 10/5 Feed in/rev. x 100


Graph of τ vs. Log of Depth
τ°
25
20
15
10
5
0
.1
.2
.3
.4
.5
.6
.7
.8
.9
LOG Depth in. x 100

Appendix D

Analysis of Variance Table Material 4340

Variation due to:	Sum of squares		Degrees of freedom		Mean square		F	
Regression	.17528369	05	.50000000	01	.35056737	04	.12699053	04
Residual	.16287415	03	.59000000	02	.27605787	01		
Total	.17691243	05	.64000000	02				

Coefficient	Value		t		Variance of coefficient	
a	.22248777	02	.67552142	01	.10847609	02
b1	.51747666	01	.23406610	01	.48876993	01
b2	.22955155-	02	.84134247-	01	.74441448	01
b3	.69830780	01	.38122272	01	.33553376	01
b4	.45028354	00	.11924459	02	.14259188	02-

x1		x2		x3		x4		y		exp y		Standardized deviate	
.19029999	01	.70800018	00	.13470001	01	.60000000	01	.27500000	02	.27952011	02	.27205037-	00
.19029999	01	.70800018	00	.13470001	01	.60000000	01	.29299805	02	.27952011	02	.81119118	00
.19029999	01	.10090027	01	.19199982	01	.60000000	01	.22700195	02	.25043743	02	.14105017-	01
.19029999	01	.10090027	01	.19199982	01	.60000000	01	.22400391	02	.25043743	02	.15909440-	01
.19029999	01	.13099976	01	.24919968	01	.60000000	01	.22500000	02	.22128670	02	.22349127	00
.19029999	01	.13099976	01	.24919968	01	.60000000	01	.20900391	02	.22128670	02	.73925950-	00
.19029999	01	.16119995	01	.30670014	01	.60000000	01	.19000000	02	.19211470	02	.12727657-	00

.16019974	01	.70800018	00	.11340027	01	.60000000	01	.31700195	02	.31661642	02	.17753284	01-
.16200027	01	.10090027	01	.16159973	01	.60000000	01	.30400391	02	.27344585	02	.14071623	01
.16019974	01	.10090027	01	.16159973	01	.60000000	01	.29299805	02	.26843651	02	.11310299	01
.16019974	01	.13099976	01	.20979996	01	.60000000	01	.22700195	02	.22025658	02	.31061651	00
.16019974	01	.13099976	01	.20979996	01	.60000000	01	.22799805	02	.22025658	02	.35648545	00
.16019974	01	.16119995	01	.25820007	01	.60000000	01	.17299805	02	.17189136	02	.50961613	01-
.16019974	01	.16119995	01	.25820007	01	.60000000	01	.17200195	02	.17189136	02	.50926700	02-
.13010025	01	.70800018	00	.92099762	00	.60000000	01	.22400391	02	.24616115	02	.10203150-	01
.13010025	01	.70800018	00	.92099762	00	.60000000	01	.21500000	02	.24616115	02	.14349342-	01
.13010025	01	.10090027	01	.13130035	01	.60000000	01	.24099609	02	.20359407	02	.17223192	01
.13010025	01	.10090027	01	.13130035	01	.60000000	01	.23200195	02	.20359407	02	.13081496	01
.13010025	01	.13099976	01	.17040024	01	.60000000	01	.18599609	02	.16109026	02	.11468843	01
.13010025	01	.13099976	01	.17040024	01	.60000000	01	.17799805	02	.16109026	02	.77858362	00
.13010025	01	.16119995	01	.20970001	01	.60000000	01	.11599609	02	.11840116	02	.11075059-	00
.13010025	01	.16119995	01	.20970001	01	.60000000	01	.11900391	02	.11840116	02	.27755634	01-
.10000000	01	.70700073	00	.70800018	00	.60000000	01	.14500000	02	.17576344	02	.14166199-	01
.10000000	01	.70800018	00	.70800018	00	.60000000	01	.13500000	02	.17570328	02	.18743381-	01

.10000000	01	.10090027	01	.10090027	01	.60000000	01	.13900391	02	.13881232	02	.88223103	02-
.10000000	01	.10090027	01	.10090027	01	.60000000	01	.10500000	02	.13881232	02	.15570175-	01
.10000000	01	.13099976	01	.13099976	01	.60000000	01	.12799805	02	.10192230	02	.12007576	01
.10000000	01	.13099976	01	.13099976	01	.60000000	01	.10900391	02	.10192230	02	.32609983	00
.10000000	01	.16119995	01	.16119995	01	.60000000	01	.69003906	01	.64908843	01	.18857283	00
.10000000	01	.16119995	01	.16119995	01	.60000000	01	.75996094	01	.64908843	01	.51055482	00
.19029999	01	.70800018	00	.13470001	01	.50000000-	01	.31500000	02	.33435565	02	.89130497-	00
.19029999	01	.70800018	00	.13470001	01	.50000000-	01	.32599609	02	.33435565	02	.38494782-	00
.19029999	01	.10090027	01	.19199982	01	.50000000-	01	.26000000	02	.28049962	02	.94398328-	00
.19029999	01	.10090027	01	.19199982	01	.50000000-	01	.24099609	02	.28049962	02	.18190908-	01
.19029999	01	.13099976	01	.24919968	01	.50000000-	01	.20200195	02	.22670638	02	.11376099-	01
.19029999	01	.13099976	01	.24919968	01	.50000000-	01	.20500000	02	.22670638	02	.99955334-	00
.19029999	01	.16119995	01	.30670014	01	.50000000-	01	.19400391	02	.17266504	02	.98262959	00
.19029999	01	.16119995	01	.30670014	01	.50000000-	01	.18700195	02	.17266504	02	.66019790	00
.16019974	01	.70800018	00	.11340027	01	.50000000-	01	.30200195	02	.26389778	02	.17546522	01
.16019974	01	.70800018	00	.11340027	01	.50000000-	01	.31799805	02	.26389778	02	.24912534	01

.16019974	01	.10090027	01	.16159973	01	.50000000-	01	.24099609	02	.21571787	02	.11640324	01
.16019974	01	.10090027	01	.16159973	01	.50000000-	01	.23799805	02	.21571787	02	.10259759	01
.16019974	01	.13099976	01	.20979996	01	.50000000-	01	.17799805	02	.16753794	02	.48167559	00
.16019974	01	.13099976	01	.20979996	01	.50000000-	01	.18599609	02	.16753794	02	.84997622	00
.16019974	01	.16119995	01	.25820007	01	.50000000-	01	.11799805	02	.11917272	02	.54092355-	01-
.16019974	01	.16119995	01	.25820007	01	.50000000-	01	.11500000	02	.11917272	02	.19214888-	00
.13010025	01	.70800018	00	.92099762	00	.50000000-	01	.17200195	02	.19344251	02	.98731239-	00
.13010025	01	.70800018	00	.92099762	00	.50000000-	01	.19000000	02	.19344251	02	.15852355-	00
.13010025	01	.10090027	01	.13130035	01	.50000000-	01	.15599609	02	.15087543	02	.23580058	00
.13010025	01	.10090027	01	.13130035	01	.50000000-	01	.15700195	02	.15087543	02	.28211922	00
.13010025	01	.13099976	01	.17040024	01	.50000000-	01	.12500000	02	.10837162	02	.76571724	00
.13010025	01	.13099976	01	.17040024	01	.50000000-	01	.13299805	02	.10837162	02	.11340179	01
.13010025	01	.16119995	01	.20970001	01	.50000000-	01	.45000000	01	.65682523	01	.95240581-	00
.13010025	01	.16119995	01	.20970001	01	.50000000-	01	.37998047	01	.65682523	01	.12748375-	01
.10000000	01	.70700073	00	.70800018	00	.50000000-	01	.13400391	02	.12304480	02	.50465417	00
.10000000	01	.70800018	00	.70800018	00	.50000000-	01	.13400391	02	.12298464	02	.50742419	00
.10000000	01	.10090027	01	.10090027	01	.50000000-	01	.89999999	01	.86093680	01	.17988139	00

.10000000	01	.10090027	01	.10090027	01	.50000000-	01	.89999999	01	.86093680	01	.17988139	00
.10000000	01	.13099976	01	.13099976	01	.50000000-	01	.45000000	01	.49203656	01	.19357341-	00
.10000000	01	.13099976	01	.13099976	01	.50000000-	01	.40000000	01	.49203656	01	.42381752-	00
.10000000	01	.16119995	01	.16119995	01	.50000000-	01	.18000000-	01	.12190204	01	.13902233-	01
.10000000	01	.16119995	01	.16119995	01	.50000000-	01	.18000000-	01	.12190204	01	.13902233-	01

Analysis of Variance Table   Material 1020

Variation due to:	Sum of squares		Degrees of freedom		Mean square		F	
Regression	.27594741	05	.50000000	01	.55189482	04	.11702896	04
Residual	.27823706	03	.59000000	02	.47158824	01		
Total	.27872978	05	.64000000	02				

Coefficient	Value		t		Variance of coefficient	
a	.44493514-	01	.10343301-	01	.18504404	02
b1	.27821389	02	.96400421	01	.83291324	01
b2	.60187691-	01	.16886496-	01	.12703877	02
b3	.62372618-	01	.26073931-	01	.57223564	01
b4	.47926036	00	.97104813	01	.24359114	02-

x1		x2		x3		x4		y		exp y		Standardized deviate	
.19029999	01	.70800018	00	.13470001	01	.60000000	01	.37799805	02	.38707429	02	.41795038-	00
.19029999	01	.70800018	00	.13470001	01	.60000000	01	.36799805	02	.38707429	02	.87843859-	00
.19029999	01	.10090027	01	.19199982	01	.60000000	01	.34500000	02	.33321826	02	.54253536	00
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